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# UNITY POWER FACTOR CORRECTION USING THE BI-BOOST TOPOLOGY WITH A FORWARD CONTROL TECHNIQUE

**Nicu BIZON, Emil SOFRON, Mihai OPROESCU**
*University of Pitesti,*
*Str. Targul din Vale Nr. 1, phone: 0248 222949, fax 216448, Pitesti,*
*e-mail nbizon@upit.ro*

***Abstract**. We propose a simple unity PFC controller by sensing only the input line voltage. The sinusoidal current waveform in phase with the DC line voltage can be obtained, but the DC output voltage regulation is relatively small. This is a consequence of the feed forward control with a little dependence by the circuit parameters. The simulation results are presented for a bi-boost converter that operate in discontinuous current mode. The PFC controller parameters were chosen after a mathematical analysis of the continuous current mode converter operation.*

***Keywords:** PFC controller, bi-boost converter, DCM, CCM*

## Introduction

Among three basic power converter topologies (boost, buck and buck-boost), the boost converter, shown in Figure 1, is the one most suitable for power factor correction (PFC) applications [1,2,3]. This is because the inductor is in series with the line input terminal through the diode rectifier, which gives lower line current ripple and continuous input current can be obtained with an average current mode control technique. As a result, a small line input filter can be used [4]. However, the output voltage has to be higher than the line input voltage for a boost converter. The buck converter is seldom used as a power factor correction application, since the input current is discontinuous and it loses control when the line input voltage is lower than the output voltage. The buck-boost and flyback converters are able to control the average line input current. However, the power handling capability is smaller because of its higher voltage and current stresses. Therefore, the boost converter is currently the most popular PFC topology. To achieve unity power factor, the input power is the squared sine waveform while the output power is usually constant for most applications. Thus, the power is unbalanced between the input and the output over half the line cycle. This unbalanced power has to be stored in an energy storage element, like the bulk capacitor. For a boost converter, the output filter capacitor, which is the only bulk capacitor, can deal with this unbalanced power. Consequently, the power has to be processed twice, which is inefficient. In addition, the cost increases because the component count increases. This is the main disadvantage for the two-stage approach.

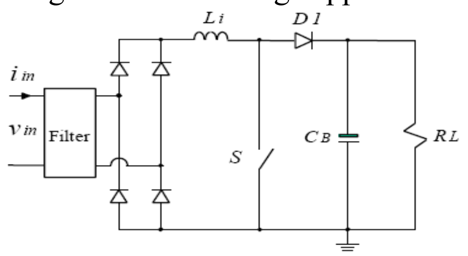



**Figure1. Power factor correction boost converter.**

In order to reduce the cost, many single-stage PFC converters, which integrate the PFC stage with the DC/DC stage into a single stage, have been proposed in last decade [5,6,7]. The main idea is that the PFC stage and DC/DC stage share a common switch so that one main switch and its controller can be saved. However, the control freedom has been reduced and only one control variable can be controlled [8,9,10]. For most applications, the output voltage has to be tightly regulated, while the power factor cannot be controlled. Thus, it requires that the PFC stage have inherent power factor correction. A good power factor can be obtained if the boost converter is operated in the discontinuous current mode (DCM), so a DCM boost converter integrated with another converter can achieve power factor correction and tight output voltage [11, 12]. In this paper we investigate the bi-boost topology possibilities to achieve a unity PFC when it's operate in DCM and using a direct control command.

## Parallel power factor correction

The main disadvantage is that high DC bus voltage stress exists at light load, if the PFC stage operates in DCM, and efficiency isn't very high (up to 60%). In a bi-boost topology the unbalanced power can be stored in the DC small capacitor at the input of the one parallel boost inductor, separated by a diode from the other boost inductor (see a flyback converter variant in Figure 2.). The two stages share a common switch S to achieve power factor correction and tight output voltage. From its circuit structure, it is actually a flyback integrated with another flyback converter. For the bi-boost converter is the same association. By choosing an optimal power flow between the bi-boost inductor we can obtain a improved efficiency and a PFC over to 0.9. To meet IEC1000-3-2 regulation, however, unity power factor is not required; 0.8 power factor is enough to meet the line current harmonics limitation [13]. However, the efficiency is still lower than the two-stage approach, mainly because of the wide range switching frequency operation. In addition, it is difficult to optimally design inductive components, like inductors and EMI filter, for wide range switching frequency operation.

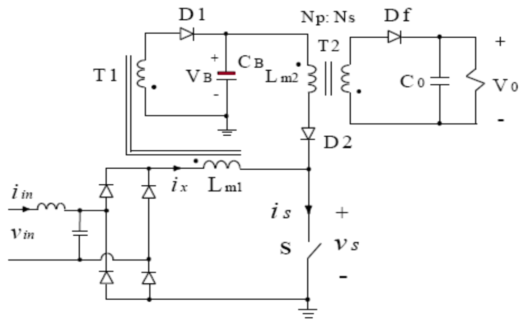



**Figure 2. Flyback converter variant.**

In this paper we test the new sensorless power factor correction controller presented in [14] than the bi-boost operate in DCM. Because the DCM boost converter has a discontinuous input current, it requires a relatively large input filter to suppress the high frequency input line current harmonics [15,16,17]. A major disadvantage of the two-stage approach is that the output power is processed twice. From the PFC standpoint, the converter does not need to process all of the power. Only a part of the output power must be processed twice, which can be realized by the parallel power factor correction (PPFC), like bi-boost structure. This PPFC scheme reveals the benefit of efficiency improvement. Usually, the realization of unity power factor with PPFC involves a very complex topology and control. However, for many low-power applications, the single-stage approach has been developed to reduce the cost. The power factor does not need to be very high for the single-stage PFC AC-DC converters as long as the input current harmonics can meet the IEC requirements. The basic topologies suffer from extreme duty ratios and severe rectifier reverse recovery. Utilizing coupled inductor is a simple solution to avoid extreme duty ratios, but the leakage inductance associated with the coupled inductor induces severe voltage stress and loss. This paper presents the bi-boost derivation (Figure 3), analysis and simulation results when the converter operates in DCM and the inductors aren't coupled. The proposed innovative control solutions can achieve significant performance improvement compared to the state-of-the-art technology for unity PFC.

## Problem statement

First we develop the PFC condition for bi-boost converter operating in DCM and after that we will test the PFC controller in DCM converter function. For a unity PFC it is necessary to have

$$v_{in} = V_{in} \sin\varphi \text{ and } i_{in} = I_{in} \sin\varphi,$$

where $\varphi = 2\pi ft, 1/f = T >> T_{PWM}$. For the PPFC that operate in CCM, shown in Figure 3, the duty ratio PWM control can be derived from:

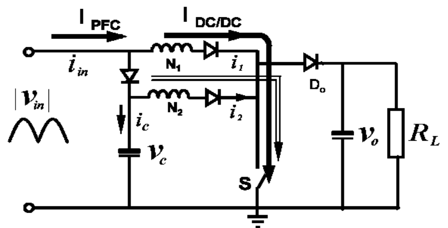



**Figure 3. Bi-boost converter variant.**

$$|v_{in}|-v_s=L_1\cdot\frac{di_1}{dt},\ v_c-v_s=L_2\cdot\frac{di_2}{dt}$$

$$\left.\begin{array}{l}|i_{in}|=i_1+i_2+i_c\\ \frac{di_c}{dt}\cong 0\ pe\ T_{PWM}\end{array}\right\}\Rightarrow\frac{d|i_{in}|}{dt}\cong\frac{di_1}{dt}+\frac{di_2}{dt}\qquad(1)$$

From above equations, by substitute the currents derivates, the PFC control relation is obtained:

$$\omega I_{in}\cos\varphi\cong\frac{|v_{in}|-v_s}{L_1}+\frac{v_c-v_s}{L_2},\ \varphi\in[0,\pi]\qquad(2)$$

Using classical notations and new others

$$k_V\overset{\Delta}{=}\frac{V_o}{V_{in}},\ k_C\overset{\Delta}{=}\frac{V_{C(AV)}}{V_{in}},\ k_L\overset{\Delta}{=}\frac{L_1}{L_2},\ Q_L=\frac{\omega L_1}{R_L}\qquad(3)$$

$$V_{s(AV)}=\beta V_o,\ \beta=1-\alpha_{PWM},\ I_{in}=\frac{2U_o^2}{\eta V_{in}R_L}$$

the PFC control relation can be rewritten as:

$$\beta V_{in}k_V\cong\frac{1}{1+k_L}V_{in}\sin\varphi+\frac{k_Lk_C}{1+k_L}V_{in}-\frac{2Q_L}{1+k_L}k_V^2V_{in}\cos\varphi\qquad(4)$$

In a compact form the PFC controller model is:

$$\beta V_{in}k_V\approx k_1V_{in}\sin\varphi+k_2V_{in}-k_3k_V^2V_{in}\cos\varphi\qquad(5)$$

Where

$$k_1=\frac{1}{1+k_L},\quad k_2=\frac{k_Lk_C}{1+k_L},\quad k_3=\frac{2Q_L/\eta}{1+k_L}\qquad(6)$$

The DC output voltage is directly controlled by the PWM command signal (see Figure 4.).

For the most situations the control component $k_3k_V^2V_{in}\cos\varphi$ is small compared with the first and second terms $k_1V_{in}\sin\varphi+\frac{k_2}{k_C}v_c$. This give as a relative small DC output voltage regulation by $k_V$ control parameter.

**Simulation results**

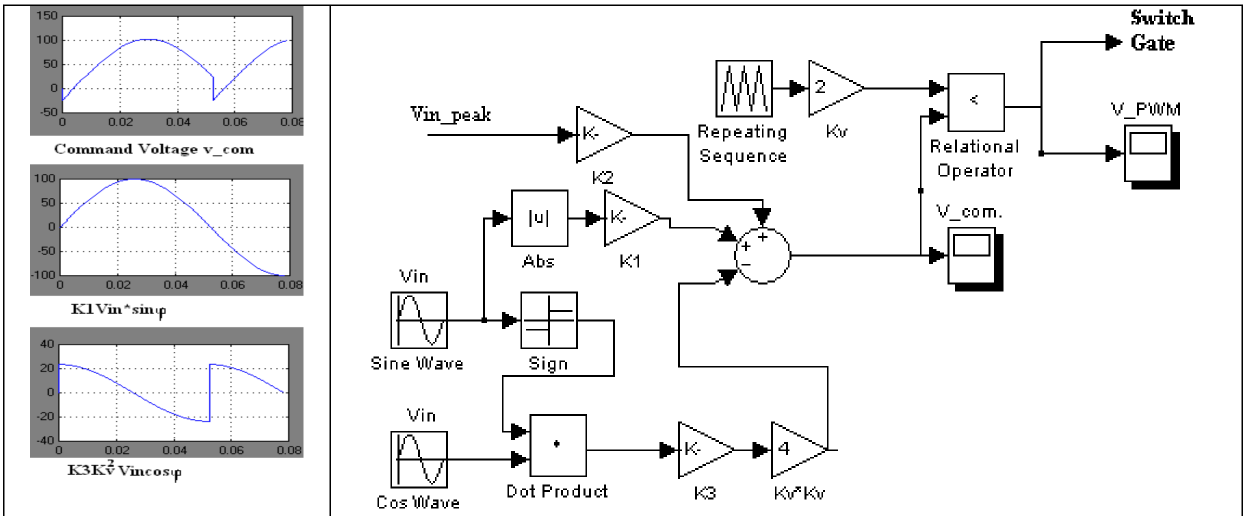
The first used values for the PWM controller are following listed:

$$V_{in}=100V,\ f_{in}=60Hz,\ k_V\overset{\Delta}{=}\frac{V_o}{V_{in}}=\frac{200V}{100V}=2,$$

$$C=1.6mF,\ k_C=\frac{\Delta V_{C(AV)}}{V_{in}}=0.8,\ Q_L=\frac{\omega L_1I_0}{V_o},\qquad(7)$$

$$I_0=4A,\ \omega=2\pi f_{in},\ C_{out}=3000\mu F$$

The sinusoidal current waveform in phase with AC line voltage can be obtained for different $k_L\overset{\Delta}{=}L_1/L_2$ values (see Figure 5.).




| Control components | PFC controller model |
|---|---|

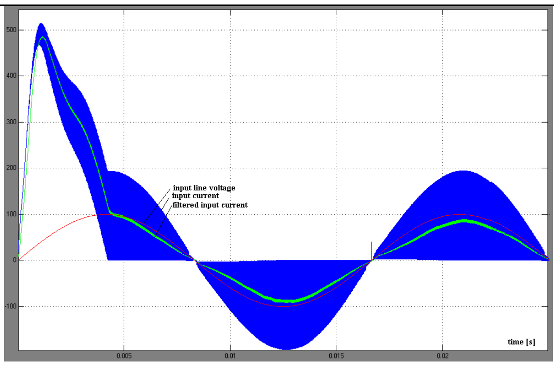
**Figure 4. Forward PFC controller.**

Because the converter operate in DCM the obtained output voltage value is bigger than expected CCM output voltage value (see Figure 6.). We test the output voltage regulation by $k_V$ parameter (see Figure 6) and we choose $k_V=2$ for the rest of the simulations. By inspecting the obtained results (partially shown in Figure 5: power factor and converter efficiency, input current harmonics and total harmonic distortion - THD) we choose the following values:

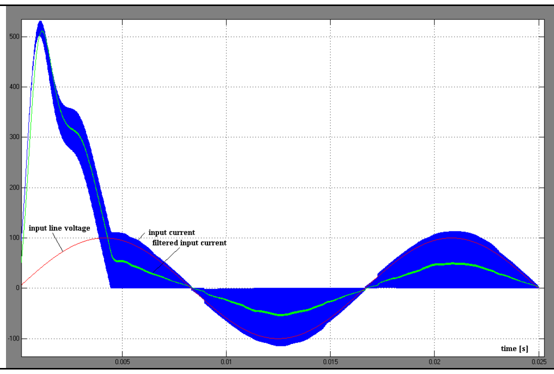
$$k_L\overset{\Delta}{=}\frac{L_1}{L_2}=\frac{0.05\mu H}{0.01\mu H}=5\Rightarrow V_{out}\approx 300V\Rightarrow\qquad(8)$$

$$\Rightarrow R_L \approx \frac{300}{4} = 75\Omega \Rightarrow Q_L = \frac{2\pi 60 \cdot 0.05\mu H}{75} \cong 0.25$$

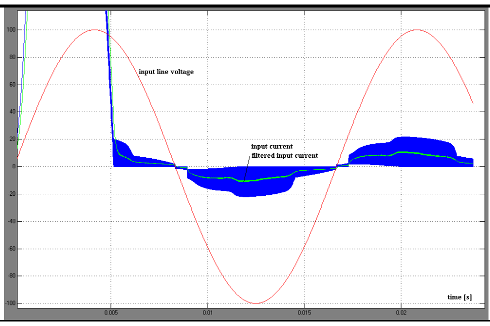
Also $k_C = \frac{\Delta V_{C(AV)}}{V_{in}}$ remain the same (see the $V_C$ waveform). For designed parameter values we test the power converter performance varying the AC line voltage $V_{in}$ (Figure 7) and output current $I_0$ (Figure 8). The modified parameter values are mention in every case.



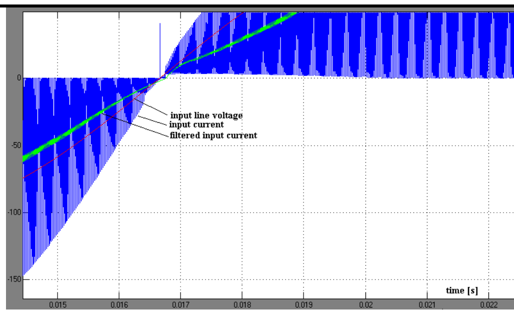

i_in: for $k_v = 2$, $k_L = \frac{0.01\mu H}{1\mu H} = 0.01$



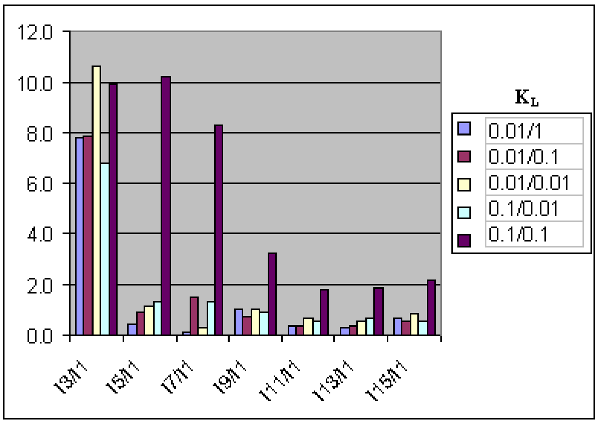

i_in: for $k_v = 2$, $k_L = \frac{0.01\mu H}{0.1\mu H} = 0.1$



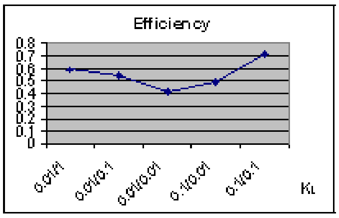

i_in: for $k_v = 2$, $k_L = \frac{0.1\mu H}{0.1\mu H} = 1$

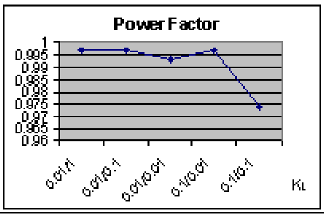



i_in – zoom: for $k_L = \frac{0.01\mu H}{0.1\mu H} = 0.1$

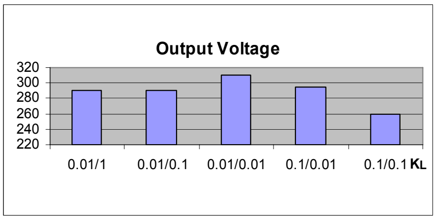


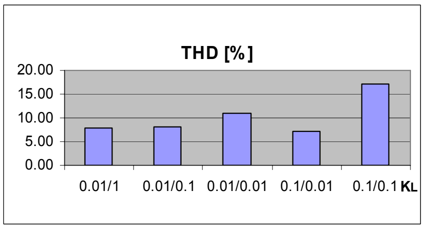

Input current harmonics [In/I1 %] for $k_v = 2$



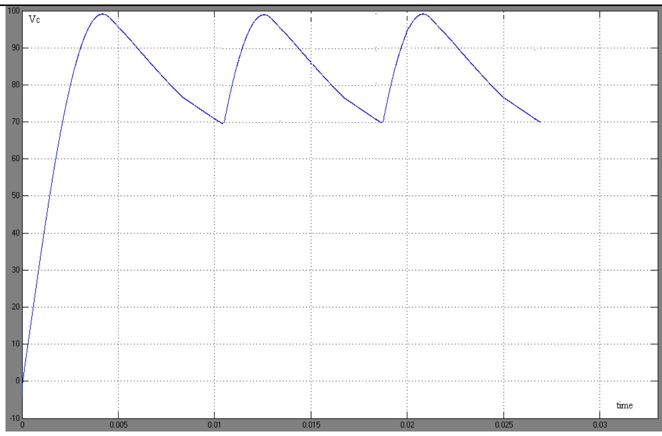




Power factor and efficiency for $k_v = 2$



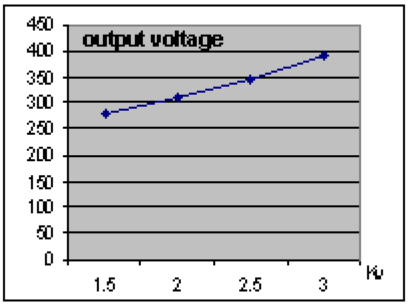




Output voltage and THD for $k_v = 2$

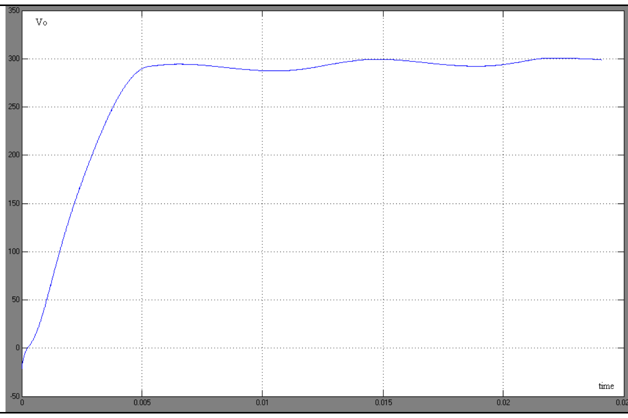



$V_C$ for $k_v = 2$

**Figure 5. Simulation results for Vin=100 V and Io=4 A.**




Output voltage regulation

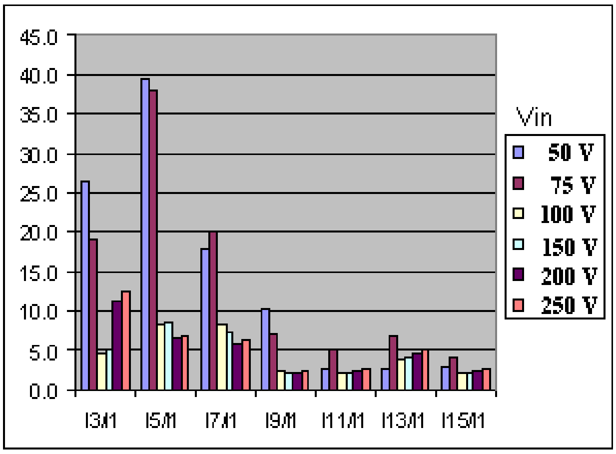



Output voltage in time for $k_v = 2$

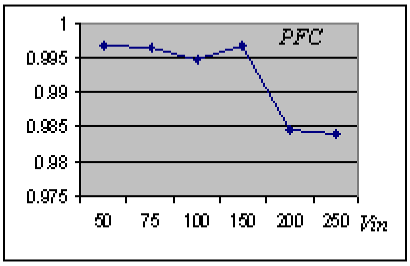
**Figure 6. Simulation results for Io=4 A, $k_C = 0.8$ and $k_L = 5$.**

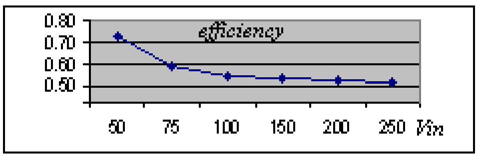
We can see from above pictures (Figure 5, 6) that:

1. Power converter operates in DCM mode for a given situation (a L1 / L2 inductor set); this change a little the expected DC output voltage, direct controlled by $k_V$ control parameter;
2. The energy conversion efficiency is around to 50% for a PFC>0.99;
3. The input current harmonics meet the IEC1000-3-2 regulations.

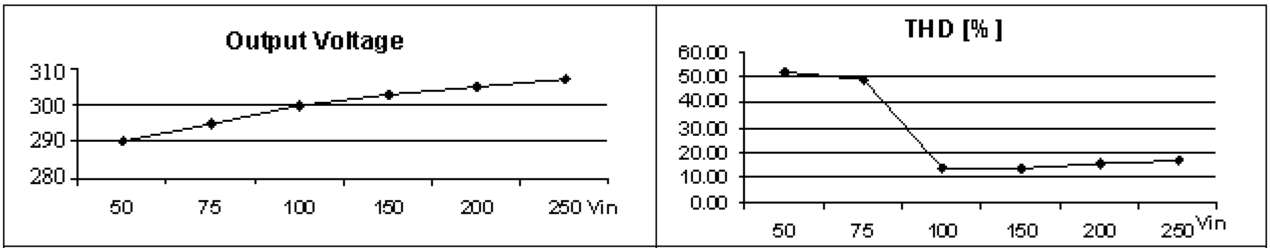



Input current harmonics [In/I1%]




Power factor and efficiency

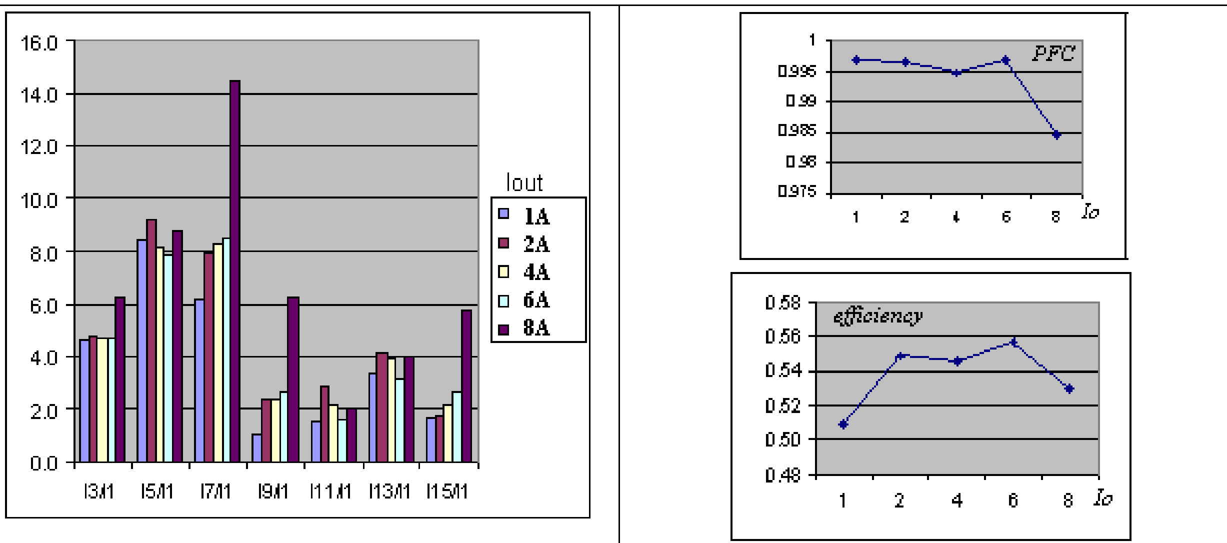



Output voltage | Total harmonic distortion

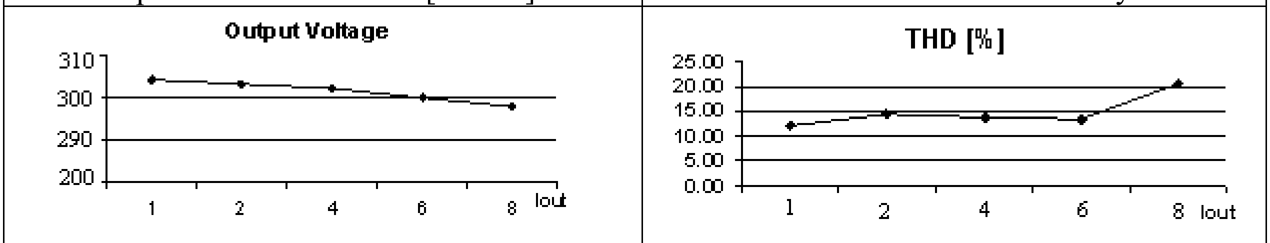
**Figure 7. Simulation results for different $V_{in}$ values (Io=4 A).**

For a large variation of the input line voltage, we observe from above pictures (Figure 7) that:

1. The shape of the input line current is almost the same the boost efficiency is almost constant with input voltage;
2. The input current harmonics meet the IEC1000-3-2 regulations for all input line voltage; The specified limits in IEC 1000-3-2 are given at 230 V. To compare the harmonic components for different input voltage, the specified limits are chanced in ratio of those voltages.
3. The output voltage sensitivity to input voltage is aprox. 100mV/V;




Input current harmonics [In/I1%] | Power factor and efficiency




Output voltage | Total harmonic distortion

**Figure 8. Simulation results for different output current $I_0$ values ($V_{in}$=100V).**

For a large variation of all output current, we observe from above pictures (Figure 7.) that:

1. The boost efficiency is over 50% for all output current values;
2. The power factor is over 0.995 for all output current values in range 1÷4 A;
3. The input current harmonics meet the IEC1000-3-2 regulations for a large load variation;

4. THD remain smaller for large output current values;

5. The output voltage PFC controller sensitivity to output current changing is reasonable (max $\Delta V_O \approx 5V$ for a $\Delta I_O = 3A$ );

**Conclusions**

By separating the input voltage source into two voltage sources connected to the two non-coupled windings, a bi-boost topology for PPFC

can be found. As determined by the turn's ratio and the input line voltage, the current selects different discharge paths. This characteristic can be used to select the current path for PPFC applications. The single-stage non-coupled-inductor PPFC converters that operate in DCM are proposed and verified. Compared to the conventional single-stage approach, in which the bulk capacitor voltage and the switch current stress are the major concerns, the proposed converters have much lower voltage stress. The bulk capacitor voltage is almost independent of the load variation.

The input current harmonics of an AC-DC converter with 100 V line input and 300V/4A output meet the IEC-1000-3-2 requirements. The conversion efficiency is up to 70% and the PFC is over to 0.99. The proposed concept can be easily extended to other AC-DC converters with different DC-DC topologies, as it requires only a few simple modifications.

The proposed solutions are verified by simulations for a 1200W PFC AC-DC boost converter. PPFC only processes a small portion of the output power twice, which brings the potential benefit of efficiency improvement when the converter operates in CCM. The state-of-the-art single-stage PFC converters that operate in DCM suffer from switching current stress problems. In some applications such dimmer power source, the DC output voltage is acceptable in a range and the load conditions do not so vary. In this case the circuit parameters can be well estimated and the PFC controller will operate near to the optimal conditions. For other applications where the output voltage must be strictly regulated we study now the control feedback effect over the PFC bi-boost performances. In stationary regime the error amplifier feedback signal is much smaller than forward control signal the preliminary results are well.

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